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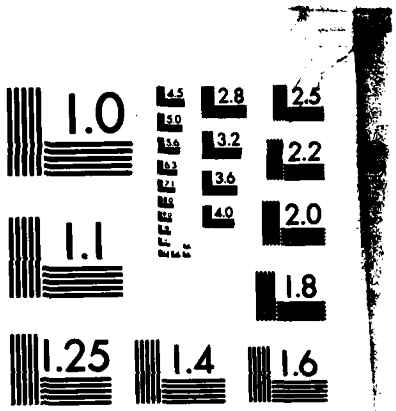

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LASER JOURNAL

(Selected Articles)

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BRANCH-SELECTED INFRARED LASER RING CAVITY
FOR ULTRA HIGH RESOLUTION SPECTROSCOPY*

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ABSTRACT

A simple method for branch-selection is suggested and the beam parameters for the cavity are calculated.

I. INTRODUCTION

There are many methods for obtaining ultra-high resolution resonance spectra [1]. However, the ultra-high resolution spectra in ring cavities possess certain special characteristics. It has been reported that this method has been used to obtain spectral lines with widths only a hundredth of the uniform linewidth [3], and to increase the frequency stability of the laser so that it is on the order of $10^{-14} \sim 10^{-15}$. Repeatability of frequency has reached 10^{-14} [4].

This type of work has chiefly been performed on He-Ne/CH_4 and He/Ne/Ne atomic laser systems. When attempting to apply this method to the infrared spectral region where there is an abundance of spectral lines, and using a ring molecular laser (such as a CO or CO_2 laser) as the light source, one is met with the following problem: What is an effective and convenient method for branch-selection that will keep the intensities of the two waves that travel in opposite directions in the ring cavity fundamentally the same, so that one has the choice of making use of any one of several competing effects.

A simple and effective solution to the above problem is provided here. A formula for calculating the beam parameters for the cavity

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and a criterion for the stability of the cavity are also given.

II. METHOD FOR BRANCH SELECTION

It is very convenient to perform branch selection using gratings. However, there is a problem. For ordinary blazed gratings, light energy is mostly concentrated near the blaze angle. Hence, a high Q value can be obtained only by placing a reflecting mirror at that angle to form a resonance cavity. We illustrate this by means of Figure 1. Assume α is the blaze angle of the grating, ψ is the angle of incidence and ϕ is the diffraction angle. Let $\psi = \alpha - x$, $\phi = \alpha + x$. From the grating equation, we have (taking a + sign for the case where the incident light and the diffracted light are on the same side of the grating normal)

$$\sin\psi + \sin\phi = 2\sin\alpha\cos x = \frac{n\lambda}{d} \qquad (1)$$

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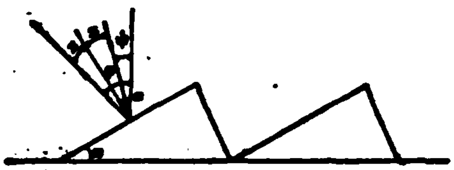

Figure 1. Blazed grating

In the above equation, d is the grating constant, λ is the wavelength, and n is the order of diffraction. For a certain wavelength to be concentrated at a certain angle, that angle has to satisfy both the grating equation and the law of reflection at the grating facets. Hence, we require that $x = 0$, i.e., $\psi = \phi$. Under this condition, the light intensity is most concentrated, and the cavity has the highest Q-value. However, this type of arrangement usually results in a stationary wave cavity. Even if the zeroth order diffraction is used to form a ring cavity, the two waves that propagate in opposite directions in the ring cavity do not have equal intensity. Therefore, this arrangement does not satisfy the requirement of equal intensities for the waves traveling in opposite directions.

To overcome the above difficulty, we present the following method. Figure 2 shows the optical path of our method. The grating performs branch selection by rotating about the 0-axis, while the

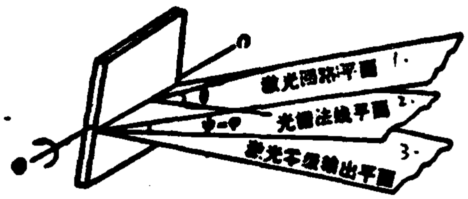

Figure 2. Branch-selection by grating in ring cavity
1--plane of laser return path
2--normal plane of grating
3--plane of zeroth-order laser output

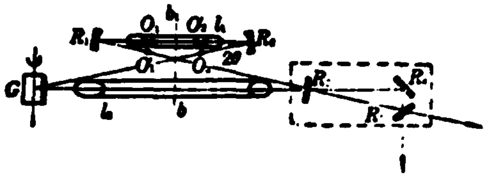

Figure 3. X-shaped ring laser cavity
R_1, R_2--spherical mirrors; R_3, R_4, R_5 plane mirrors; G--grating;
l_1--gain tube; l_2--absorption tube

return path of the laser always lies in the first-order diffraction plane of the grating. No matter what orientation the grating is in, the angle of reflection θ of the laser at the grating remains the same. Therefore, such a structure not only ensures the equality of the angle of incidence ψ to the diffraction angle ϕ (hence a very high Q-value), but also fulfills the requirement of having equal intensities of the two waves that travel in opposite directions. Favorable conditions are thus established for high resolution resonances to occur in the ring cavity. The coupled output of the laser is determined by the quality of the grating. If the efficiency of the first-order diffraction of the grating is very high, then the transmitted coupled output is taken. On the other hand, if the grating has a larger zeroth-order diffraction coupling, then the zeroth-order coupled output is taken.

III. DESIGN OF THE OPTICAL CAVITY

1. Selection of cavity shape

Gaseous laser ring cavities usually have a triangular or rectangular shape. One or several spherical mirrors are usually placed inside the cavity to increase its stability. As light is incident on or reflected from spherical mirrors at relatively large angles, spherical and comet aberrations are inevitable. These have adverse effects on laser oscillation and beam characteristics.

To overcome this difficulty, we can use a symmetrical X-shaped ring cavity structure. This helps to reduce the angle of reflection of light rays off the spherical mirrors, which in turn reduces spherical aberration and automatically compensates for comet aberration [5]. Naturally, a new problem arises here, viz., that of a smaller ratio of optical path length in the gain medium to that in the non-gain medium. Thus, we are faced with the possibility of increased influence of atmospheric convection, ambient temperature and vibrations on the cavity frequencies. Furthermore, when the cavity length frequency spread $\Delta\nu_L$ is less than the gain line width $\Delta\nu_G$, i.e.,

$$\Delta\nu_L = \frac{c}{L} < \Delta\nu_G \text{ Hz} \tag{2}$$

multi-mode oscillation will result. In the above equation, L is the length of the cavity; c is the speed of light. This problem can be solved by using a secondary cavity, as shown in Figure 3. As long as the cavity length frequency spread of the secondary cavity $\Delta\nu_l = \frac{c}{l}$ (l is the length of the secondary cavity) satisfies the inequality below

$$\Delta\nu_l > \Delta\nu_G > \Delta\nu_L \text{ Hz} \tag{3}$$

a single longitudinal-mode oscillation will be obtained. Moreover, stability of the laser frequency can be achieved by taking care of the frequency stability of the secondary cavity. This has a definite significance in the frequency stabilization of high power ring lasers.

2. Calculation of the parameters for the X-shaped oscillation cavity

It is in general necessary to install a gain tube and an absorption tube inside the cavity of a ring laser used for studying ultra-high resolution laser spectra. Therefore, it is appropriate to employ a cavity as shown in Figure 3. Under the premise that this cavity satisfies the stability criterion [6]

$$-1 < \frac{A+D}{2} < 1 \tag{3'}$$

(where A and D are the component matrices of the ABCD optical matrix of the ring cavity), one can easily determine the other parameters of the harmonic oscillation cavity by means of the method of parameter separation described in [7]. These parameters can, of course, be obtained from the ABCD matrix also.

For example, assume that we wish to design a symmetrical X-shaped CO_2 ring laser cavity. The stability criterion of such a cavity is obtained from equation (3) and reads

$$\left.\begin{array}{l} \dfrac{L_1L_2}{2(L_1+L_2)}<f<\dfrac{L_1}{2} \\ \text{or} \\ f>\dfrac{L_2}{2} \end{array}\right\} \qquad (4)$$

L_1 is the distance between the two spherical mirrors; L_2 is the remainder of the cavity length; $f = f_1 = f_2 = \frac{R}{2}$ is the focal length of the spherical mirrors.

Based on the condition of self-supporting propagation in the cavity (Figure 3), the following relations exist among the confocal parameters of the Gaussian beam [7]:

$$b_1=b_2=\sqrt{2}f^2/l_{12} \qquad (5)$$

and

$$l_1=l_2=(1-\sqrt{2}/2)f^2/l_{12} \qquad (6)$$

In the above, l_1 is the distance between the waist and the left focal point 0_1 of R_1, on the left side of 0_1; l_2 is the distance between the waist and the right focal point $0'_2$ of R_2, on the right side of $0'_2$; l_{12} is the distance between the focal points $0'_1$ and 0_2. This Gaussian beam has another waist midway between $0'_1$ and 0_2, with its confocal parameter given by

$$b=(\sqrt{2}+1)l_{12} \qquad (7)$$

Moreover,

$$l_{12}=l_1+l_2=(2-\sqrt{2})\frac{f^2}{l_{12}} \qquad (8)$$

Obviously, the total cavity length is

$$L = l_{11} + l_{12} + 4f, \tag{9}$$

and the bore of the waist is given by

$$2\omega_1 = 2\sqrt{\frac{\lambda b_1}{2\pi}}. \tag{10}$$

The above relations can be used to determine the parameters of the resonator, such as range of stability, position and diameter of the waist, etc. In the study of laser spectra, there are two choices. For single photon resonance transfers, it is usually required to have low laser power. In order to reduce collisions and line broadening, very low absorption pressure and relatively large beam diameter are desired. This can be achieved by taking a small f and a large l_{12}, and placing the absorption tube in this longer arm, and the gain tube in the short arm. On the other hand, for double photon resonance transfers, a high laser power is required. Therefore, this can be achieved by interchanging the gain tube and absorption tube positions. For example, under the condition that the stability criterion is satisfied, let $f = 0.3$ m and $l_{12} = 4.0$. From equation (5), we obtain $b_1 = 0.04$ m. From equation (10), we get $2\omega_1 \approx 0.5$ mm (taking $\lambda = 10$ μm). From equation (7), $b = 9.66$ m, $2\omega = 7.8$ mm, $l_{11} \approx 141$ mm. The total cavity length is $L = 5.214$ m. If the gain tube is 0.6 m long, then a CO_2 laser power higher than 5 watt can be obtained. The absorption tube can be made 1.2 m long, taking the tube diameter to be $2\omega/0.3 = 26$ mm. For spectral studies that require high laser intensity, one can further reduce b_1 and increase l_{12}, so that the power density at the waist in the short arm reaches 400 watt/mm^2. Although this is not difficult to achieve, it would be more reasonable to employ fluorescence detection techniques to collect spectral information under these conditions.

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TRANSMISSION DIRECTIONALITY OF LASER MODES*

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ABSTRACT

Uncertainty relation $\Delta S \Delta \Omega > \lambda^2$ can be used to discuss the directionality of laser light with TEM_{00} mode. But it can't be used in describing the directionality of laser light with higher order modes. If oscillation of laser light is considered as the linear harmonic oscillator of photons oscillating in a resonator, the uncertainty relation of laser light with higher order modes can be obtained, and this is in agreement with available experimental results.

During a conference [1] on several fundamental problems related to lasers, the problem of using the uncertainty principle to study the transmission directionality of Gaussian beams was brought up, and difficulties arose in the case of higher order modes. We analyze this problem specifically in this paper. The uncertainty principle that we usually refer to take various forms: $\Delta x \Delta p_x > \hbar$, $\Delta \phi \Delta J_z > \hbar$, $\Delta t \Delta E > \hbar \cdots\cdots$, etc. All these express the impossibility of simultaneously determining conjugate pairs of parameters, such as the position and momentum of microscopic particles, the angular coordinate and angular momentum of these particles, and time and energy. Applying this to photon statistics, we see that a photon mode occupies the volume of the photon and the three-dimensional uncertainty relation is given by

$$\Delta x \Delta p_x \Delta y \Delta p_y \Delta z \Delta p_z > \hbar^3 \qquad (1)$$

Let z be the direction of propagation of the light beam, and we have $\Delta z \Delta p_z > \hbar$, . Let $\Delta x \Delta y = \Delta S$ be the cross-section of the mode. As $p = \hbar k$. $\Delta p_x \Delta p_y = \hbar^2 \Delta k_x \Delta k_y = \hbar^2 k^2 \Delta\theta_x \Delta\theta_y$, . $\Delta\theta_x \Delta\theta_y$ is obviously directly proportional to the solid angle $\Delta\Omega$ of the transverse spreading of the mode.

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Neglecting the constant proportionality factor, one can write equation (1) as

$$\Delta S \Delta \Omega > \lambda^2 \qquad (2)$$

The above relation was first obtained by Wang Chi-chiang in 1963 in his discussion on minimum distinguishable photon states [2]. Equation (2) is commonly used in studies related to the directionality of diffraction of gratings in optical systems, and in discussions on transmission directionality of laser modes [3]. As was mentioned above, this relation is congruent with the uncertainty relation. However, difficulties arise when one attempts to use this relation to study non-TEM_{oo} mode high-mode transmission directionality. Actually, when the higher order mode is congruent with the TEM_{oo} mode at the mode cross-section ΔS, the deviation of the beam from the optic axis is much larger than the angle $\Delta\Omega$ described in equation (2). It is very important to understand this phenomenon and to derive a more general relation.

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It is well known that Heisenberg's uncertainty relations are obtained under the condition of the least wave envelope. If we let $\alpha = x-\bar{x}$ be the deviation in the position of the microscopic particle, $\beta = p=\bar{p}$ be the deviation in momentum, and the form of the wave envelope be

$$\psi(x) = [2\pi(\Delta x)^2]^{-1/4} \exp\left[-\frac{(x-\bar{x})^2}{4\Delta x^2} + \frac{i\bar{p}x}{\hbar}\right] \qquad (3)$$

then we can derive from

$$(\Delta x)^2(\Delta p)^2 = \int_{-\infty}^{\infty}\psi^*\alpha^2\psi\,dx \int_{-\infty}^{\infty}\psi^*\beta^2\psi\,dx \qquad (4)$$

the uncertainty relation

$$(\Delta x)^2(\Delta p)^2 > \frac{1}{4}\hbar^2$$

or

$$\Delta x \Delta p > \frac{1}{2}\hbar \qquad (5)$$

In fact, this relation has been obtained because equation (3) was taken to be the wave envelope, and it was assumed that $\alpha\psi = \gamma\beta\psi$ where γ is a constant coefficient, thus causing a functional factor to disappear:

$$\int \psi^* (\alpha\beta + \beta\alpha) \psi dx = 0$$

It is clear that if the wave envelope was not in the Gaussian form given by equation (3), one would have obtained a different uncertainty quantity.

The lowest order mode of a laser has a Gaussian photon distribution. It goes without saying the equation (2) is applicable to this situation. The critical oscillation of a laser is the loss-free oscillation of single photons in the harmonic oscillation cavity. In the early stages of the invention of lasers, the laser oscillations were already regarded as the oscillations of linear oscillators of a microscopic particle system [4]. In fact, the mode distribution of wave functions of the linear harmonic oscillators of a microsystem, both being described in terms of Hermite polynomials. The uncertainty relation $\Delta x \Delta p > \frac{1}{2}\hbar$ can only be used to describe the lowest order mode of the microscopic motion of the harmonic oscillators. It is not suitable for higher order modes. If we substitute the nth order wave function $u_n(x)$ of the oscillator into equation (4), then the uncertainty relation becomes [5]

$$\Delta x \Delta p > \left(n + \frac{1}{2}\right)\hbar \qquad (6)$$

This is obviously the most general form of the uncertainty relation for the motion of harmonic oscillators. When n = 0, corresponding to the lowest order mode, the relation becomes that given in equation (5). Thus, we see that the uncertainty quantity increases with increasing order of the mode (6). By the same token, equation (2) should be replaced by

$$\Delta S \Delta \Omega > \left(n + \frac{1}{2}\right)^2 \lambda^2 \qquad (7)$$

For n = 0, the above relation is the same as equation (2) except for the constant factor $(1/2)^2$. Equation (7) shows that the angular dispersion of the higher order modes increase parabolically as the

order number. This agrees with the directionality $\Delta\Omega$ obtained from calculations of the higher order mode distribution [6]. It has been pointed out in [6] that for $n<4$ $\Delta\Omega$ is directly proportional to n^2, while for $n > 4$, as more energy of the transverse modes becomes concentrated near the axis, larger deviations have been obtained because of the rejection of the diffused energy distribution in the larger outer regions. The uncertainty relations of quantum mechanics are statistical results obtained by taking the entire accessible region of the photons into consideration and are, therefore, of greater generality.

Equation (7) shows that suppressing higher order modes, so that energy becomes concentrated in the lowest order mode, is advantageous for propagation, and greatly increases the brightness of the beam. It also expresses the inseparability of the uncertainty in the lowest order mode from the quantized zero-point energy $\frac{1}{2}\hbar\omega$ of the light field. This effect becomes very small for the higher order modes.

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